ADVANCED CARBON-MODIFIED POLYMERS: INNOVATIONS IN SUSTAINABLE MATERIALS

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Abstract

Microplastic pollution resulting from the degradation and wear of polymer materials has become one of the major environmental concerns associated with the widespread use of plastics. In this study, thermoplastic polymers based on acrylonitrile-butadiene-styrene (ABS), polylactic acid (PLA), and polycarbonate (PC) were modified with carbon-based additives, namely DTX (selectively ion-modified activated carbon) used as a functional carbon filler and wood-derived activated carbon, and evaluated under accelerated aging conditions. The aim of the work was to determine how these modifiers affect the aging behavior, color stability, and surface condition of the investigated materials. The specimens were prepared by injection molding and then exposed to accelerated aging in a Xenotest climatic chamber under Arizona test conditions. Optical stability was monitored by color measurements expressed as L*, a*, b*, and total color difference ΔEab, while surface-related changes were examined by scanning electron microscopy (SEM). The results showed that the modified formulations exhibited lower ΔEab values than the corresponding reference materials, indicating improved color stability during aging. SEM observations confirmed that accelerated aging induced degradation-related features, including microcracks, local peeling, delamination, and surface irregularities, although the extent and character of these changes depended on both the polymer matrix and the type of modifier used. The results indicate that carbon-based modification can improve the aging resistance of thermoplastic polymers, particularly in terms of optical stability, while also influencing the development of surface degradation during exposure. These findings suggest that the effectiveness of the modifiers is strongly formulation-dependent.

Keywords: *microplastics; activated carbon; thermoplastic polymers; sustainable materials*

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Introduction

Microplastic pollution has emerged as a critical environmental issue associated with the extensive production, utilization, and disposal of polymeric materials. In addition to primary microplastics intentionally manufactured at microscopic dimensions, a substantial fraction of environmental contamination originates from secondary microplastics generated during the service life of polymer products. These particles are formed as a result of physicochemical degradation processes, including mechanical abrasion, oxidative reactions, and progressive surface fragmentation. Such mechanisms not only deteriorate the structural integrity and functional performance of polymer systems but also promote the continuous release of fine particulate matter into environmental compartments [1-3].

The rapidly increasing scientific interest in this problem is clearly reflected in bibliometric trends. A Scopus-based analysis using the keyword “microplastics” identified 32,746 documents published between 1978 and 2025. Notably, while only a single publication was recorded in 1978, a significant and sustained increase in research output has been observed since 2015, reaching several thousand papers annually (Fig. 1). This exponential growth highlights the urgent need for the development of advanced polymeric materials with enhanced resistance to degradation and reduced propensity for microplastic generation.

One of the promising strategies to improve the durability and environmental stability of polymeric materials involves the incorporation of carbon-based modifiers into thermoplastic matrices. In particular, carbonaceous fillers derived from sustainable and renewable sources have attracted considerable attention due to their tunable surface chemistry, hierarchical porosity, and particle size distribution, which govern interfacial interactions within polymer–filler systems. These features significantly influence the mechanical performance, thermal stability, and resistance to environmental degradation of the resulting composites [4]. Among the various carbon-based materials, activated carbon and wood-derived carbon are of particular interest, as they may contribute not only to properties enhancement but also to improved structural stability under environmental exposure and mechanical loading conditions. From the perspective of biomaterials engineering, the durability and surface stability of polymeric materials are important not only for implantable systems, but also for a wide range of non-implantable biomedical and user-contact applications. Thermoplastic polymers are commonly considered for medical equipment housings, rehabilitation accessories, protective elements, diagnostic components, aquatic and sport-related devices, and other polymer parts exposed to direct contact with users or demanding environmental conditions. In such applications, materials may be exposed to ultraviolet radiation, humidity, elevated temperature, disinfectants, chlorinated water, mechanical wear, and long-term surface degradation. These factors can affect not only the visual appearance of the material, but also its surface integrity, aging resistance, and potential tendency to release small degradation products or microplastic-like fragments. Therefore, improving the resistance of thermoplastic polymers to aging-induced optical and surface changes is relevant to the development of more durable and environmentally responsible materials for selected biomaterial-related applications.

It should be emphasized that the final properties of polymer composites are determined not only by their chemical composition but also by the processing route applied during fabrication. Processing conditions affect the internal microstructure, dispersion of the filler phase, and surface characteristics, which in turn influence the material’s response

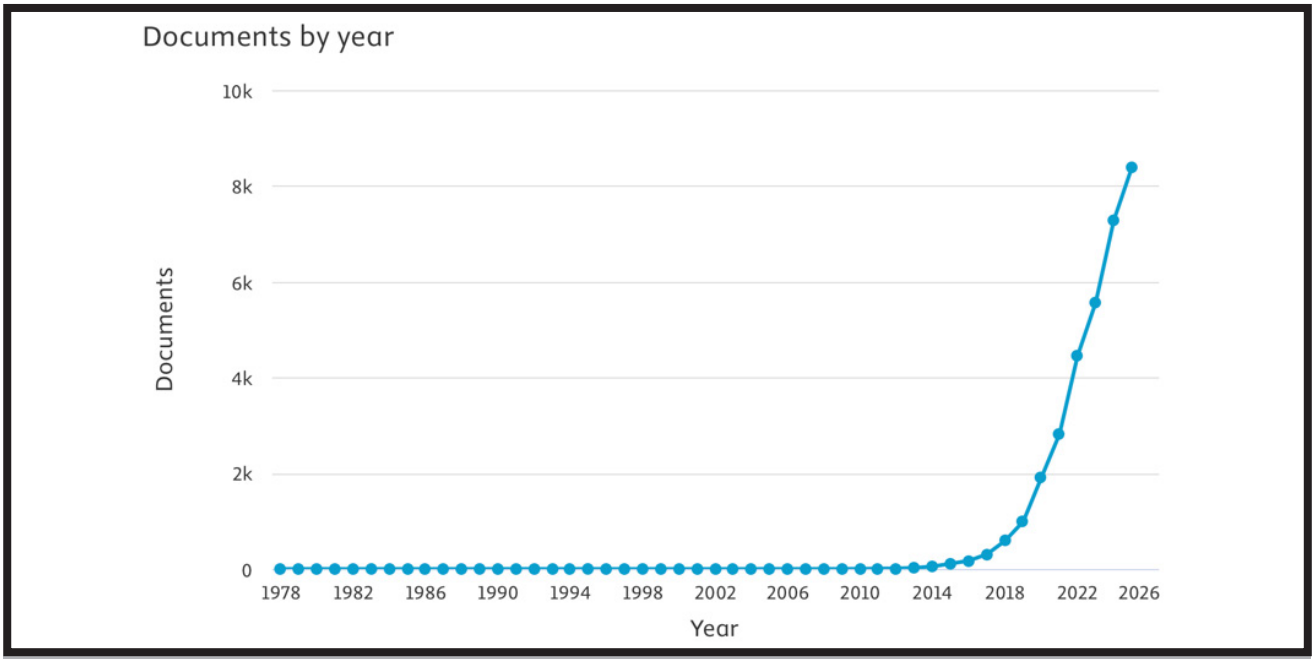

FIG. 1. Annual number of Scopus-indexed documents retrieved for the search term "microplastics" in the years 1978-2025. The search returned 32,746 documents. Source: Scopus database.

to environmental stressors. Previous studies have demonstrated that different processing techniques can lead to substantial variations in the physical and mechanical properties of identical polymer systems [5-7]. Consequently, materials of the same nominal composition may exhibit significantly different performance and aging behavior depending on the applied manufacturing methodology.

Since degradation processes typically initiate at the material surface and progressively propagate into the bulk, surface-sensitive analytical techniques are essential for the evaluation of aging phenomena. In this context, colorimetric analysis and scanning electron microscopy (SEM) provide complementary insights into optical and morphological changes. Optical stability can be quantitatively assessed using the CIELAB color space parameters (L*, a*, b*), where L* represents lightness, a* corresponds to the red–green axis, and b* describes the yellow–blue axis. The total color difference (ΔE*ab) serves as an integrative parameter reflecting the overall extent of color change during exposure [8, 9]. In parallel, SEM enables detailed characterization of surface morphology, allowing the identification of microscale degradation features such as microcracks, pits, and surface irregularities.

In light of the above considerations, the present study focuses on thermoplastic polymers modified with activated carbon and wood-derived carbon, with particular emphasis on their aging behavior, color stability, and surface condition under controlled exposure conditions. Furthermore, ongoing research aims to extend this analysis by comparing different processing routes, including additive manufacturing and injection molding, to elucidate their influence on the long-term performance and environmental resistance of carbon-modified polymer systems. In this context, the investigated carbon-modified polymers may be considered as candidate materials for selected external biomedical, rehabilitation, protective, and user-contact applications, where long-term environmental stability and limited surface degradation are required.

Materials and Methods

Acrylonitrile–butadiene–styrene (ABS), polylactic acid (PLA), and polycarbonate (PC) were employed as thermoplastic polymer matrices in this study. The investigated systems were modified with carbon-based additives, namely DTX and wood-derived activated carbon, to evaluate their influence on material performance under controlled aging conditions. The number of formulations included in the final experimental set differed among the ABS-, PLA-, and PC-based systems. This was related to differences in processing behavior, repeatability of specimen preparation, and the selection of formulations that remained suitable for further aging, colorimetric, and microscopic evaluation. In particular, the PLA-based series was limited to two modified formulations in addition to the reference sample, because not all prepared variants provided specimens of sufficient quality and reproducibility for the full test procedure.

Before processing, the polymer matrices in granular form were mechanically blended with the selected carbonaceous modifiers in predetermined proportions. In a representative formulation, the polymer matrix, carbon modifier, and polyol were combined at a weight ratio of 1.00:0.05:0.01, respectively. The components were introduced into a 3000 cm³ stainless steel mixing reactor equipped with an electrostatic discharge protection system and maintained at 25 °C. Homogenization was performed using a Teflon stirrer with scraping blades at 50 rpm for 30 min, yielding a visually uniform mixture devoid of observable agglomerates. Subsequently, the prepared blends were subjected to aerostatic drying at 100 °C for 24 h under reduced pressure to eliminate residual moisture and promote structural stabilization.

Test specimens were fabricated by injection molding using a Battenfeld Plus 35/75 UNILOG B2 injection molding machine. Before molding, the materials were dried under conditions appropriate for each polymer matrix to ensure optimal processing behavior. Injection parameters, including barrel temperature profile and mold temperature, were adjusted according to the specific polymer and composite formulation. [10] Processing temperatures were generally maintained within the range of 180-315 °C, while mold temperatures were controlled between 40 and 90 °C, depending on the material system. The molded specimens had dimensions of 6 × 6 cm, a thickness of 1 mm, and a black color. These conditions ensured proper melt flow, homogenization, and formation of defect-free specimens suitable for subsequent analyses.

Following fabrication, the specimens were subjected to accelerated aging in a xenon arc climatic chamber under Arizona test conditions to simulate long-term environmental exposure. The aging protocol was conducted using three lamps, each delivering a UV irradiance of 60 W/m². The black panel temperature was maintained at 65 °C, while the chamber temperature and relative humidity were controlled at 38 °C and 17%, respectively. The total exposure time was set to 4000 h. [11]

Surface morphology and degradation-related changes were evaluated by scanning electron microscopy (SEM) using a Hitachi SU8010 microscope. The SEM images analyzed in this study were acquired at an accelerating voltage of 10.0 kV, at a magnification of 1.00k, in LM(UL) mode, with a scale bar of 50.0 µm. This analysis enabled the identification of microscale features such as surface cracking, pitting, and other structural irregularities associated with aging processes.

The aging behavior of the investigated materials was further assessed by colorimetric analysis using a 3Color CP100 colorimeter. Measurements were performed at regular intervals during exposure in order to monitor time-dependent changes in optical properties. The evaluated parameters included L* (lightness), a* (red–green coordinate), and b* (yellow–blue coordinate) within the CIELAB color space. The total color difference (ΔE*ab) was calculated as a quantitative measure of overall color variation and used as an indicator of material stability under accelerated environmental conditions.

Results and Discussion

SEM micrographs recorded before and after accelerated aging revealed clear changes in the morphology of the injection-molded materials under investigation. The reference samples exhibited a compact structure with limited surface irregularities. After exposure in the xenotest, the surfaces became more heterogeneous and showed features typical of degradation, including fine microcracks, local peeling, small material losses, and scattered debris. The extent of these changes depended on both the polymer matrix and the type of carbon-based modifier.

In the PLA-based materials, aging led to visible deterioration of the surface layer in both investigated formulations. In the PLA sample modified with DTX, the post-aging micrograph showed fine cracking and local flaking, indicating embrittlement. Similar degradation features were observed in the PLA sample modified with wood-derived carbon, which also showed aging-induced cracking and local delamination of the outer layer. These observations indicate that, for both PLA-based materials, the degradation process manifested as crack formation and surface peeling.

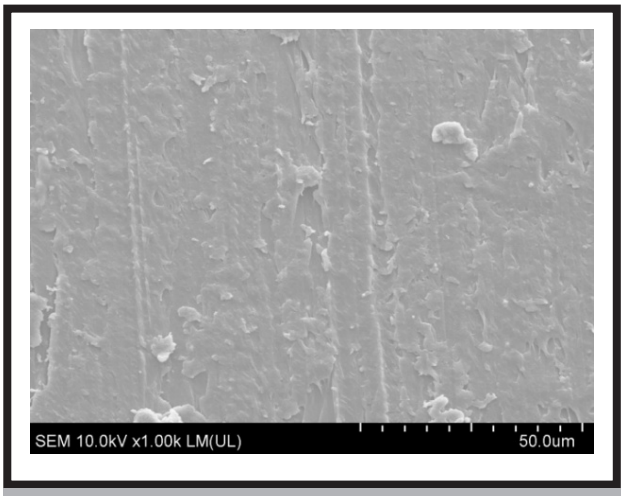

FIG. 2. SEM micrograph of the reference PLA sample.

TABLE 1. Composition and designation of polymer samples modified with carbon-based additives.

Sample name	Polymer matrix	Carbon additive	Plasticizer	Weight ratio
PLA	PLA	none	D2002	1.00:0.00:0.01
PLA/DTX	PLA	DTX	D2002	1.00:0.05:0.01
PLA/Wood	PLA	wood-derived carbon	D2002	1.00:0.05:0.01
ABS	ABS	none	D2002	1.00:0.00:0.01
ABS/DTX/1	ABS	DTX	D2002	1.00:0.10:0.01
ABS/DTX/2	ABS	DTX	D2002	1.00:0.025:0.01
ABS/Wood/1	ABS	wood-derived carbon	D2002	1.00:0.10:0.01
ABS/Wood/2	ABS	wood-derived carbon	D2002	1.00:0.025:0.01
PC	PC	none	D2002	1.00:0.00:0.01
PC/DTX/1	PC	DTX	D2002	1.00:0.10:0.01
PC/DTX/2	PC	DTX	D2002	1.00:0.05:0.01
PC/DTX/3	PC	DTX	D2002	1.00:0.025:0.01
PC/Wood/1	PC	wood-derived carbon	D2002	1.00:0.10:0.01
PC/Wood/2	PC	wood-derived carbon	D2002	1.00:0.05:0.01
PC/Wood/3	PC	wood-derived carbon	D2002	1.00:0.025:0.01

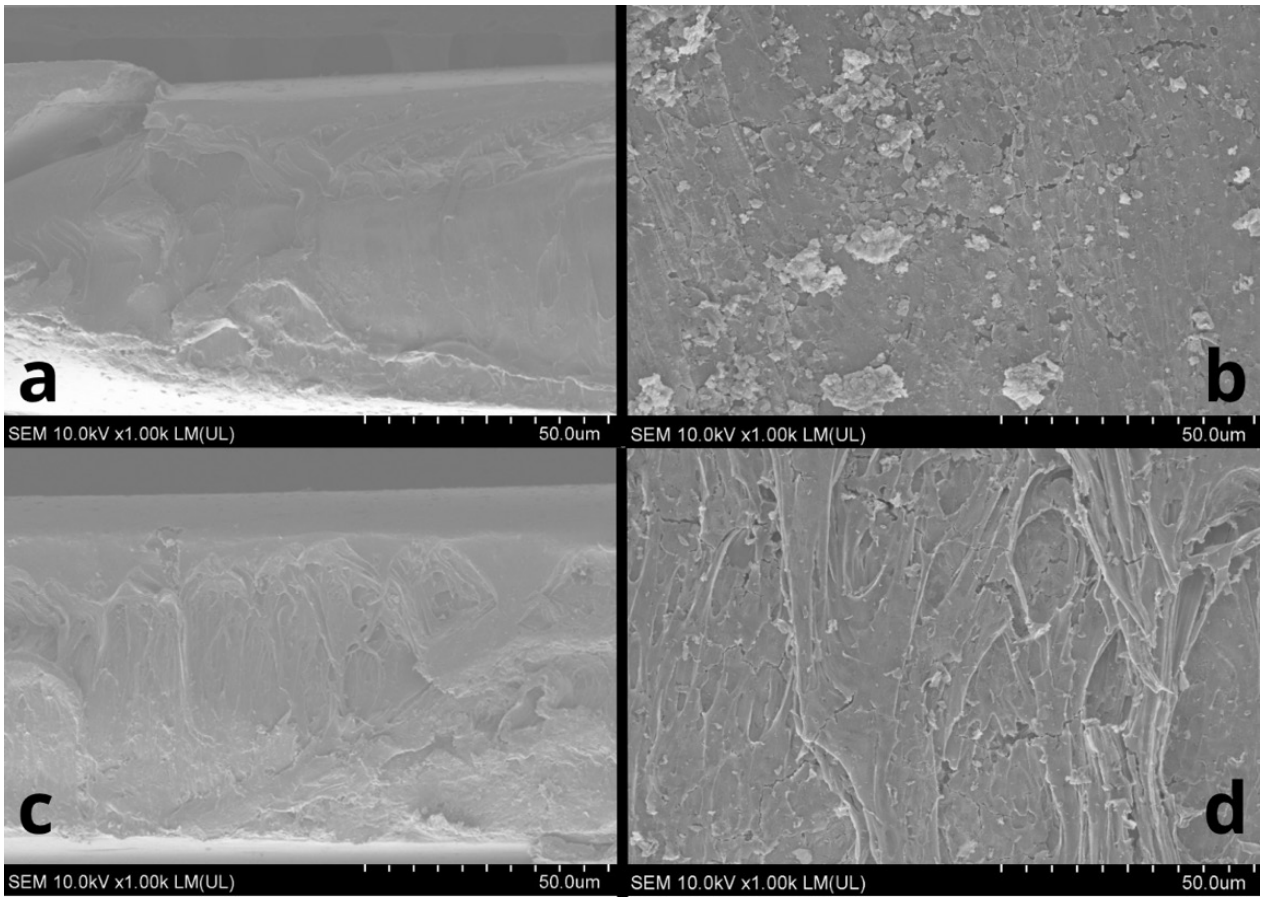

FIG. 3. SEM micrographs of PLA-based materials before and after accelerated aging: (a) reference PLA sample modified with DTX, (b) PLA sample modified with DTX after aging, (c) reference PLA sample modified with wood-derived carbon, (d) PLA sample modified with wood-derived carbon after aging.

The ABS-based materials exhibited the highest resistance to accelerated aging. In both modified formulations, the post-aging SEM micrographs showed only limited surface alterations, while the overall structure remained compact and coherent. The ABS sample modified with DTX displayed minor local defects and slight peeling, whereas the sample containing wood-derived carbon showed only subtle, evenly distributed surface irregularities. No pronounced cracking, extensive delamination, or major material loss was observed.

The most distinct contrast was observed for the PC-based materials. After aging, the PC sample modified with DTX retained a comparatively smooth and continuous surface, with only very fine microcracks and isolated defects visible at higher magnification. In contrast, the PC sample modified with wood-derived carbon showed extensive flaking and more advanced delamination, indicating greater structural deterioration after exposure. These results suggest that, within the PC matrix, the formulation modified with DTX showed better surface stability under the applied aging

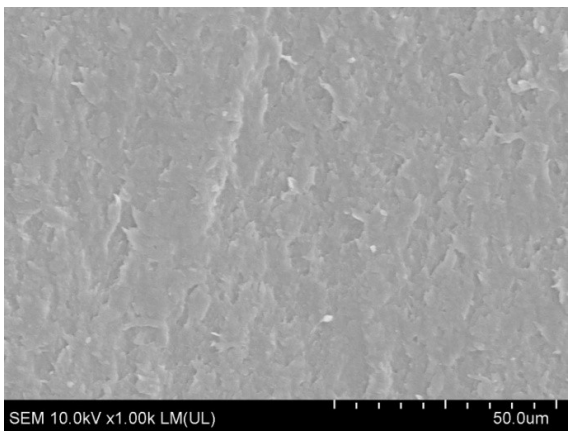

FIG. 4. SEM micrograph of the reference PLA sample.

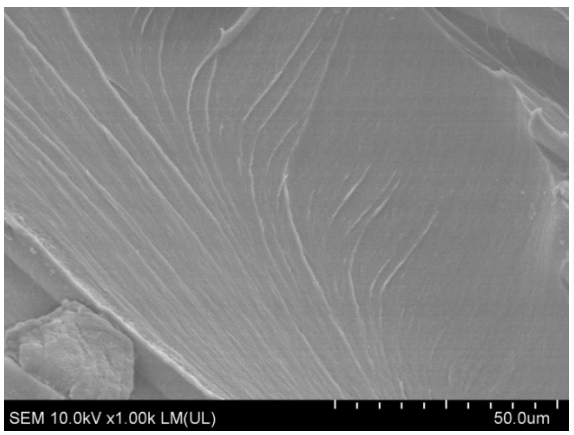

FIG. 6. SEM micrograph of the reference PLA sample.

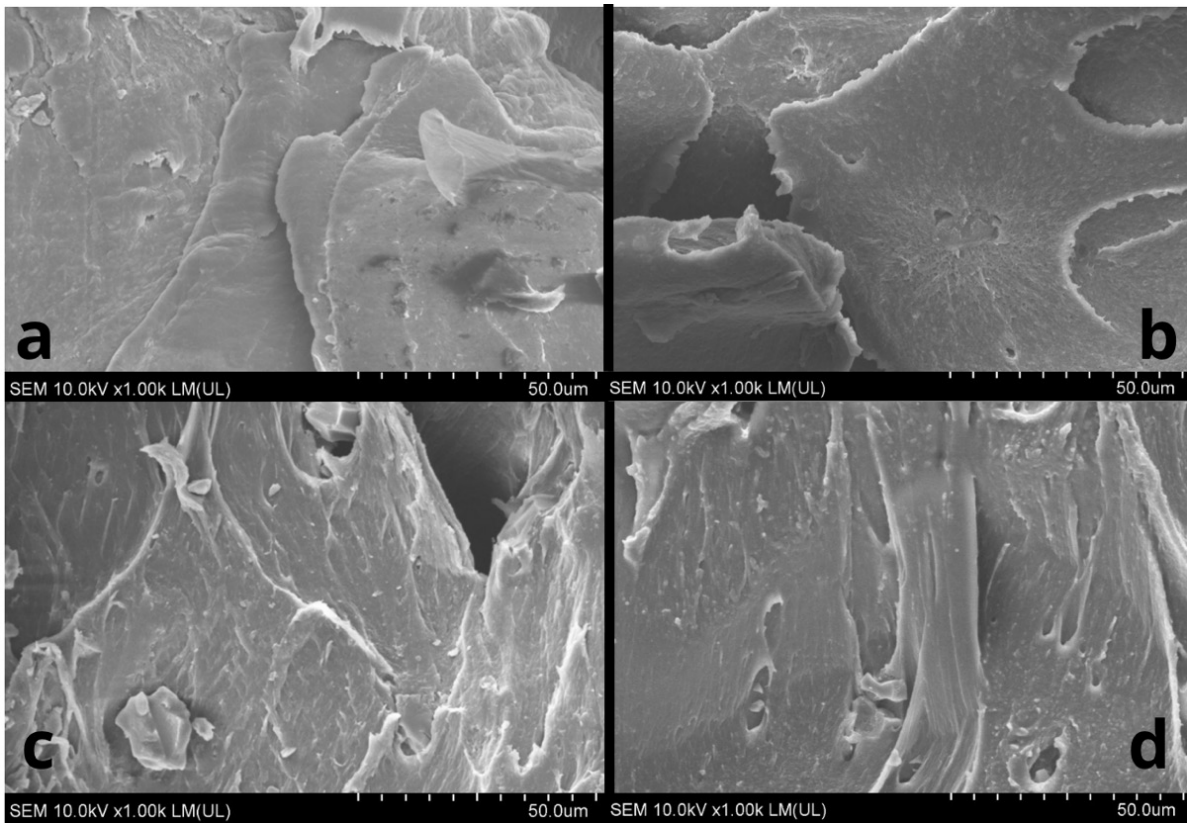

FIG. 5. SEM micrographs of ABS-based materials before and after accelerated aging: (a) reference ABS sample modified with DTX, (b) ABS sample modified with DTX after aging, (c) reference ABS sample modified with wood-derived carbon, (d) ABS sample modified with wood-derived carbon after aging.

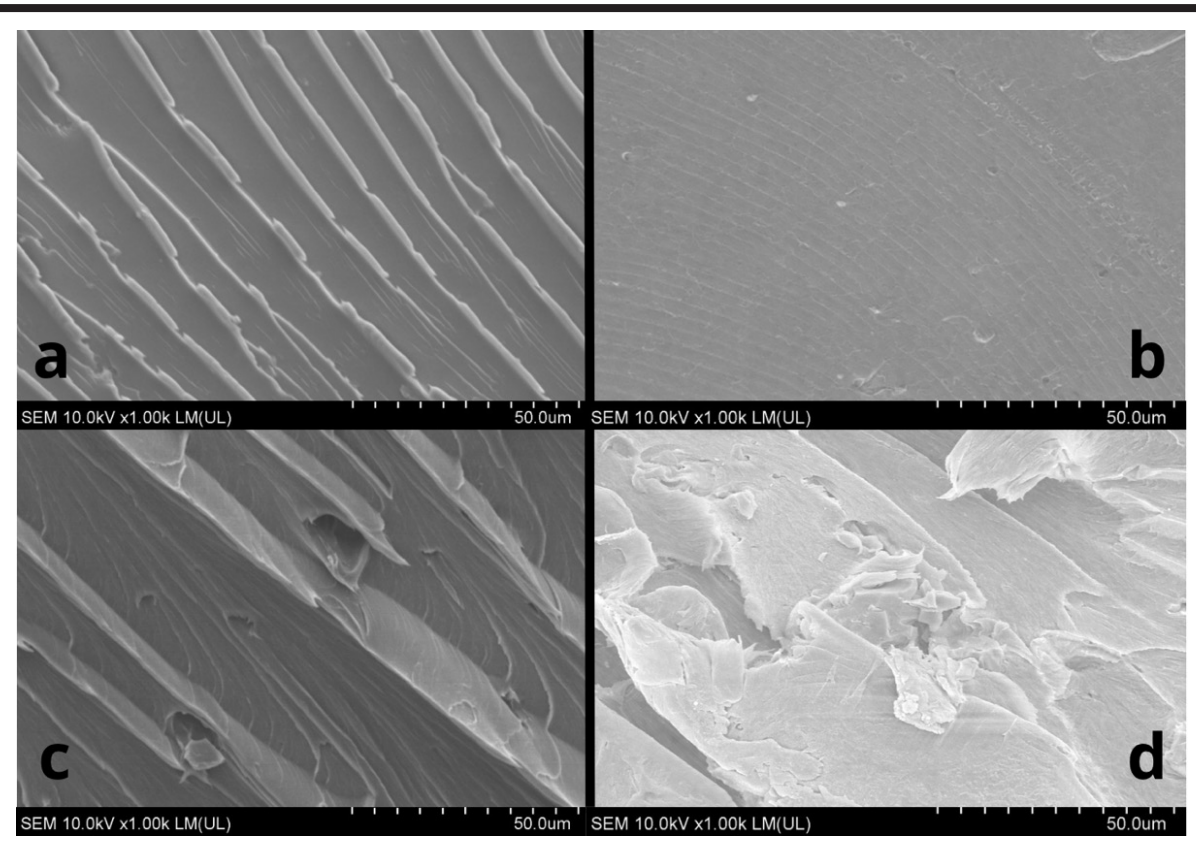

FIG. 7. SEM micrographs of PC-based materials before and after accelerated aging: (a) reference PC sample modified with DTX, (b) PC sample modified with DTX after aging, (c) reference PC sample modified with wood--derived carbon, and (d) PC sample modified with wood-derived carbon after aging.

conditions than the corresponding formulation containing wood-derived carbon.

The SEM observations confirmed that accelerated aging induced visible changes in the surface morphology of the investigated materials. Depending on the polymer matrix and the type of modifier used, the aged samples exhibited features such as microcracks, local peeling, delamination, and varying degrees of surface irregularities. The micrographs also showed that the degradation process did not proceed uniformly for all formulations, indicating different levels of resistance to aging.

The aging behavior of the investigated polymer systems was evaluated based on color measurements. Changes were expressed as the total color difference ΔEab, which was used as an indicator of optical stability during exposure. Lower ΔEab values correspond to better color stability, whereas higher values indicate more pronounced aging-related optical changes.

To further develop the analysis of the total color difference, the final ΔE*ab values obtained after the complete aging period are summarized in Table 2. The percentage reduction was calculated in relation to the corresponding unmodified reference sample for each polymer matrix. In all investigated material groups, the carbon-modified samples exhibited lower final ΔE*ab values than the reference materials, confirming their improved optical stability under accelerated aging conditions. The reference ABS and PC samples showed the highest final ΔE*ab values, equal to 16.11, which indicates the most pronounced aging-induced color change. In contrast, the lowest final ΔE*ab values were recorded for PLA/Wood, ABS/DTX/2, PC/Wood/1, and PC/Wood/2. The strongest stabilizing effect was observed for PC/Wood/2, for which the final color difference was reduced by 97.7% compared with the reference PC sample. These results confirm that the effectiveness of carbon-based modification depends on

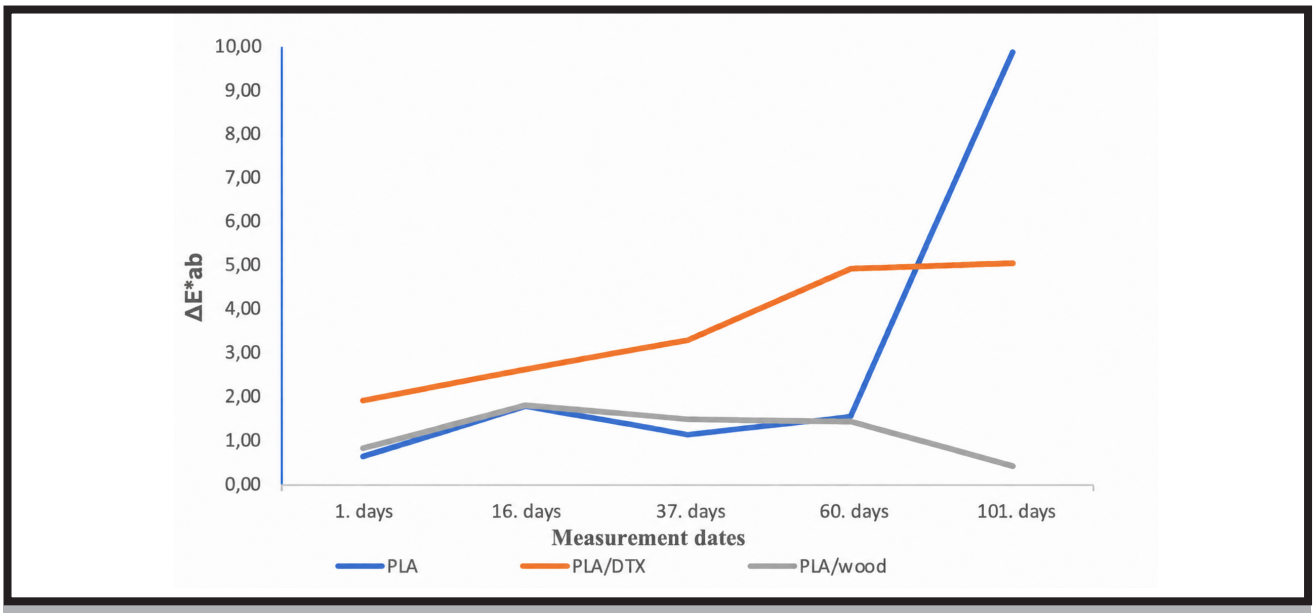

FIG. 8. Real-time total color difference (ΔE*ab) changes during measurements for samples with PLA matrix.

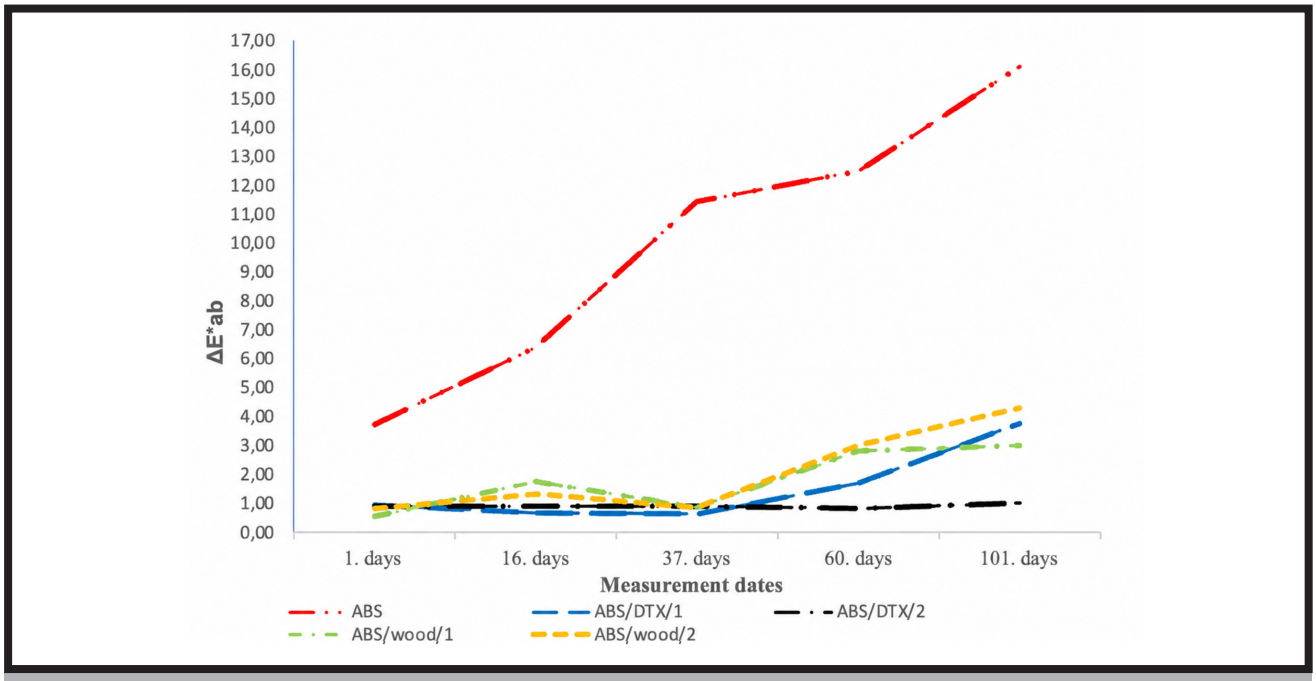

FIG. 9. Real-time total color difference (ΔE*ab) changes during measurements for samples with ABS matrix.

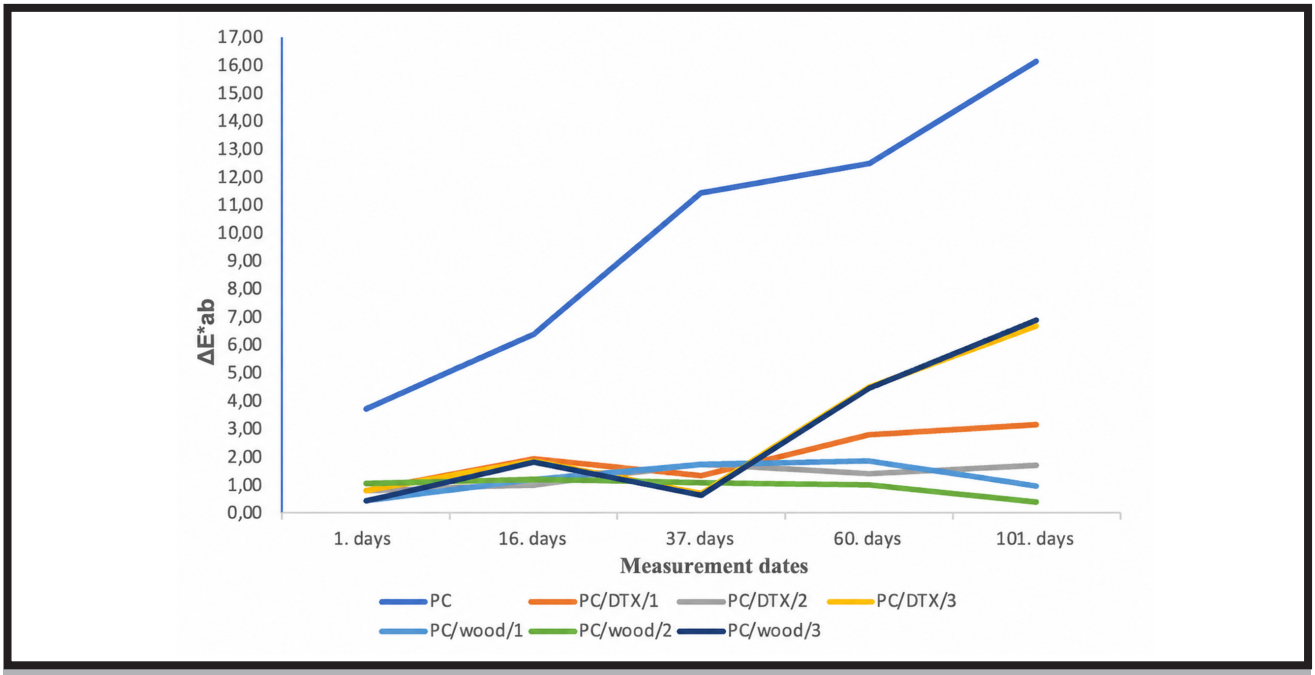

FIG. 10. Real-time total color difference (ΔE*ab) changes during measurements for samples with PC matrix.

the polymer matrix, modifier type, and modifier concentration.

Therefore, the additional numerical comparison confirms the trend observed in Figures 5-7 and demonstrates that carbon-based additives can significantly limit aging-induced optical changes in selected thermoplastic polymer systems. Figures 5-7 show the time-dependent changes in ΔE*ab for PLA-, ABS-, and PC-based materials during accelerated aging. In all three material groups, the reference samples showed the greatest overall color change, indicating lower color stability than the modified formulations. By contrast, the addition of carbon-based modifiers generally reduced the extent of aging-induced color change, although the magnitude of this effect depended on both the polymer matrix and the modifier used.

In the PLA series, the reference sample remained at relatively low ΔEab values during the early stages of aging, but a sharp increase was observed at the final measurement

TABLE 2. Major material classes used in cardiac assist devices and their key properties

Sample name	Polymer matrix	Final ΔE*ab value	Reduction relative to reference sample [%]
PLA	PLA	9.87	-
PLA/DTX	PLA	5.03	49.0
PLA/Wood	PLA	0.44	95.6
ABS	ABS	16.11	-
ABS/DTX/1	ABS	3.76	76.6
ABS/DTX/2	ABS	1.01	93.8
ABS/Wood/1	ABS	3.00	81.4
ABS/Wood/2	ABS	4.30	73.3
PC	PC	16.11	-
PC/DTX/1	PC	3.15	80.4
PC/DTX/2	PC	1.70	89.5
PC/DTX/3	PC	6.67	58.6
PC/Wood/1	PC	0.96	94.0
PC/Wood/2	PC	0.37	97.7
PC/Wood/3	PC	6.86	57.4

point, where it reached the highest value in the group. The PLA/DTX formulation showed a gradual and continuous increase throughout the test, reaching a moderate final value. The PLA/wood sample was the most stable in this series, maintaining low ΔEab values throughout the experiment and achieving the lowest final value. These results suggest that, among PLA-based materials, the wood-derived modifier had the greatest effect on color stability. A clearer stabilizing effect was observed for the ABS-based materials. The reference ABS sample exhibited a continuous increase in ΔEab over the whole aging period and reached by far the highest value in this group. All modified ABS formulations remained markedly below the reference sample. Among them, ABS/DTX/2 showed the highest color stability, with only minimal changes recorded throughout the test. ABS/DTX/1, ABS/wood/1, and ABS/wood/2 showed a moderate increase at later stages of aging, but their final ΔEab values were still much lower than those of unmodified ABS. This indicates that the modifiers effectively improved the color stability of the ABS matrix under accelerated aging conditions. The same general tendency was found for the PC-based materials. The reference PC sample showed a strong, progressive increase in ΔEab, reaching the highest final value across the entire PC series. Most modified PC formulations remained at distinctly lower levels, confirming improved color stability after modification. PC/wood/1 and PC/wood/2 showed the lowest ΔEab values and therefore the best stability during aging. PC/DTX/1 also remained clearly below the reference sample and showed only a moderate increase over time. In contrast, PC/DTX/2, PC/DTX/3, and PC/wood/3 showed a more pronounced rise at later stages of exposure, although their final values remained considerably lower than those of neat PC.

This shows that the improvement in color stability depended not only on the matrix itself, but also on the specific formulation. Overall, the color measurements indicate that the unmodified polymer matrices were more susceptible to aging-induced color change, whereas the modified materials generally retained better color stability. The most favorable effect of modification was observed in the ABS- and PC-based systems, whereas within the PLA group, the best performance was obtained with the wood-modified sample.

Conclusions

The present study showed that accelerated aging led to visible changes in both the surface morphology and color stability of the investigated thermoplastic materials. The SEM observations confirmed that the aging process induced degradation-related features, including microcracks, local peeling, delamination, and surface irregularities, although the extent and character of these changes depended on both the polymer matrix and the type of carbon-based modifier used. [12-14]

Among the investigated systems, the modified formulations generally showed better resistance to aging-induced color change than the corresponding reference materials. In all three polymer groups, the unmodified samples exhibited the highest ΔE*ab values, indicating lower color stability during exposure. The carbon-based modifiers, therefore, had a beneficial effect on the optical stability of the materials, although the magnitude of this effect varied with composition.

The results indicate that carbon-based modification can improve the aging resistance of thermoplastic polymers, especially in terms of color stability, while also influencing the development of surface degradation during exposure. The observed effects were strongly dependent on the polymer matrix and the specific formulation. Further work should include a broader analysis of the relationships among composition, processing route, and long-term durability to better assess the potential of these materials for applications requiring improved environmental stability.

Acknowledgements

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